ROUGHNESS ANALYSIS METHODOLOGY FOR PAVEMENT SURFACE BASED ON ELECTRICAL ANALOGY

Prof. Sugoog Shon
The University of Suwon, Department of Information and Telecommunication
Wau-ri Bongdam-eup San 2-2, Hwasung-si, Gyeonggi-do, Korea
sshon@suwon.ac.kr

Ph.D Inkyoon Yoo, Soohyung Lee, Jewon Kim
Korea Institute of Construction Technology, Highway Facility Research Division
2311 Daewha-Dong Ilsan-gu Goyang-si, Gyeonggi-do, Korea
ikyoo@kict.re.kr, shlee1@kict.re.kr, jewonkim@kict.re.kr

ABSTRACT

Traditional measurement methods for road pavement roughness have to use a heavy mechanical device. Its characteristics also keep change dependent on the mechanic dynamics and times it has elapsed. In this paper, electrical circuits based on RLC linear devices are proposed to analyze how road profiles affects road roughness, mechanical dynamics, and driver's fatigue. The electrical circuit method based on the analogy of the electro-mechanics does not change with mechanical dynamics, with times elapsed, or makes the calculation and understanding for the IRI easy. Research results show that the quarter car model based on the analogy can be utilized

KEYWORDS

California type profilograph, WLAN, PrI, wavelength response, TCP/IP protocol stack

1. INTRODUCTION

The interaction between heavy vehicle and road roughness results in vibrations that make drivers or passengers feel uncomfortable and cause dynamic wheel loads to increase to wear.

Driving speed plays key role on the vibrations and comfortableness of the vehicle. Resonances of the vehicle body occurred from the combined frequency characteristics between the vehicle and the pavement surface may also cause severe vibrations, reduce the life of the pavement, and lose controllability of the driver.

Road managers should have to manage the conditions of the road and try to keep the road smooth as possible as. As a road management technology, some indices related to the road roughness have been

used. PrI, IRI, and RN are the examples. Most of nations are using the traditional indexes based on the road roughness which are calculated from the road profile.

The road profile is measured by using a special equipment, which is used to characterize the dynamics of a vehicle due to the road roughness.

The profile index (PrI), one of road roughness indices, is measured by the California profilograph [1]. Another roughness index, IRI, is measured by an inertial test vehicle or others.

In the past, road managers have taken the road profile measurements and calculated the road roughness. Roads are managed by the criteria of the road roughness. They don’t manage the roads in terms of the riding comfort of a driver. As driving speed is increased, pavement surface condition is getting important. Body vibrations of drivers and the life of the pavement are more sensitive to the speed.

According to previous researches, no claim is made that the roughness or riding quality of a pavement is directly or completely reflected by the profile index.

The California profilograph doesn’t measure the riding quality and the profile index doesn’t reflect the “Riding Comfort” of a roadway. Because it’s front and rear wheels are in contact with the pavement surface, the profilograph cannot accurately measure the pavement profile. Some of the roughnesses that hides inside the 0.2” blanking band cause drivers to experience roughness.

Even if the California profilograph with 25-foot wheelbase doesn’t accurately determine the riding comfort of a roadway, most of nations have used the California profilograph to decide the roughness measurement of the road.

Think about how many drivers drive a car with 25-foot wheelbase. The California profilograph had been invented about 1960’s but it is still used these days. Response type devices such as BPR roughmeter have been devised to measure the riding comfort [2]. But there are problems that it is hard to get the same results twice, it depends on tire size, type, and pressure, and it also depends on driver, mechanical characteristic of shock and springs. All these factors change over time.

International Roughness Index (IRI) that had been devised around 1982 by the support of the World Bank is widely used around the world to measure. International Roughness Index was calculated from the quarter-car filter at a simulated speed of 80 km/hr with “golden car” parameters using pavement profile as input [3]. “Golden car” is a set of parameters for the referenced quarter-car computerized response system. Its true value is determined by obtaining a suitably accurate measurement of the profile of the road, processing it through an algorithm that simulates the way a reference vehicle would respond to the roughness inputs, and accumulating the suspension travel.

When the ARS is calculated using the Quarter-Car Simulation @ 80 km/hr, it is known as the RARS80, or IRI [4]. Average Rectified Slope (ARS) is the ratio of the accumulated suspension motion of a vehicle

(in, mm, etc) divided by the distance traveled by the vehicle during the test. Problems with response type devices are hard to get the same results twice (tire size, type, pressure, shocks/springs(change over time), driver, mechanical.

Recently, some researches have been done to investigate and find a new management technology for pavement which can explain about the relation between body vibrations and road roughness. As an example, Transport Canada has proposed a draft for a Canadian standard of pavement roughness, using the Riding Comfort Index (RCI), based on IRI and RMSVA (Root Mean Square Vertical Acceleration).

In this paper, a new roughness analysis methodology for pavement surface which will make the relationship between the road profile and the driver's fatigue is proposed. The method will be based on electrical circuits by using the analogy of the electro-mechanics. All the mechanical components are transformed into the electrical analogy components.

2. MODEL FOR NEW METHOD

The figure 1 shows relations between road qualities and its indices. As a ride quality index, vibration or RN is used. As a road roughness index, IRI or PrI is used. And Rod, Dip-stick, profilograph, walk profilograph, etc. is used as a profile measurement device.

Before we start to discuss about new method, some important factors should be mentioned. First, new method may have to include the concept of the minimum health and safety requirements into the pavement management. The sixteenth individual Directive within the meaning of Article 16(1) of Directive 89/391/EEC explains about the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (vibration) [5].

According to the highway pavement roughness research [6][7], the wave length of pavement profile has been proven to be a factor affecting an automobile's vertical response. So, although the IRI has been used in the assessment of highway pavement roughness, research should be done to compare the vertical acceleration of vehicles at given pavement profile wave lengths.

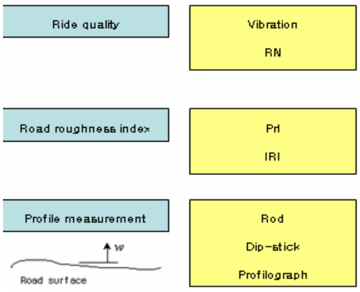


Figure 1 Road quality and corresponding index

The new methodologies should explain the relationship between vehicle's vertical accelerations and pavement profile wave lengths.

IRI's suitability for smart highway where vehicle may drive more than 120km/h has to be discussed. So, the new methodology should count affects of the wave number responses of quarter-car filter with "golden car" parameters at higher speeds. Relation between IRI and vehicle's vibration responses should be investigated according to the pavement wave lengths at higher speed.

Vehicle’s vertical accelerations with respect to wave numbers are investigated. Fred Mannering [8] linked physical quantitative roadway measures with subjective, driver-perceived measures of roughness on urban highways. He indicated that IRI is the single best predictor of driver-perceived road roughness and driver acceptability. IRI and the speed of vehicle are deeply associated with driver-perceived measures of road roughness. As an empirical data, the IRI acceptability threshold of 2.7 m/km is recommended by the Federal Highway Administration in USA.

Basically, ride comfort depends on human responses to vibrations, vehicle responses to road, road roughness. Human responses to vibrations : vital organs in the abdominal cavity resonates about at 5 Hz, A human head resonates at about 25Hz, Human eyes resonate at 30-80Hz, It is tough to grip a steering wheel if it is moving at 50-200Hz [9].

In order to investigate the relation between the road profile and body vibrations, an analysis model is designed, where, as the body vibration model, the simplified human body vibration model designed by R.R. Coermann is used. The simplified mechanical system represents the human body standing (or sitting) on a vertically vibrating platform. The figure 2 shows the analysis model.

In order to find the relation between the road profile and human body vibrations, the Quarter-car model is considered. Most of researches and management technologies have been focused on the relation between the road profile and dynamics of the vehicle, or the relation between driver’s fatigue and the vehicle’s vibration. However, the relation between the road profile and driver’s fatigue is not much investigated.

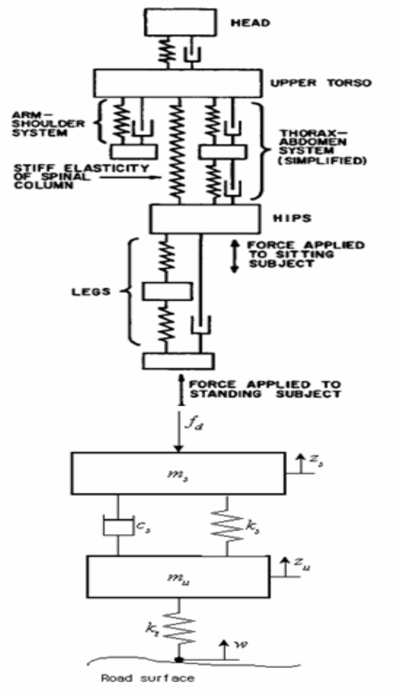


Figure 2 combined analysis model

The proposed model uses the golden quarter car model, which means that the characteristics of the car do not change over time. Unchangeable dynamics with respect to the road profile can be obtained.

3. DEVELOPING ANALOGY MODEL

The proposed combined model should be simulated, implemented, and validated. Quarter-car model can not be implemented because the mechanical dynamics change over time. However simulation can be made for the model. For the further analysis, the combined model has to be converted into an electrical circuit model.

In this paper force-voltage analogy is used, which is convenient to represent a circuit topology. The parenthesis shows the analogy term based on the force-current analogy.

The force-voltage analogy between electrical and mechanical networks can be set up by means of the following correspondences:

Force ←→ voltage (current) Displacement ←→ charge (flux)

Damper ←→ resistor (resistor) Spring ←→ capacitor (inductor)

Mass ←→ inductor (capacitor)

The mechanical quarter-car model can be implemented with electrical circuit components such as resistor, capacitor, or inductor, which gives unchangeable and robust results because the electrical circuits components do not change over time, practically speaking.

The following figure 3 shows the relationship between mechanical dynamic components and electrical basic circuit elements. In the force-voltage analogy, mass corresponds to inductor, friction to resistor, spring to capacitor.

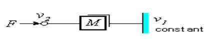
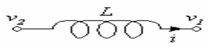
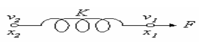
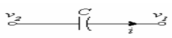
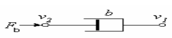
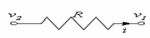
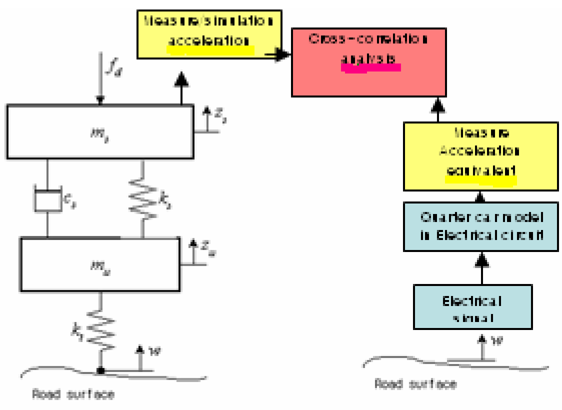
- mass  F = M dv/dt
- inductor  V_{21} = L di /dt
- Spring  F_k = k X_{21}
- capacitor  I = C dV_{21}/dt
- friction  F_b = b V_{21}
- resistor  V_{21} = I R

Figure 3 Force-current analogy

Figure 4 shows the concept to convert and validate the equivalent analogy circuit. First, the equivalent circuit model is built from the dynamic quarter-car model. Some investigations is made how the road surface profile affects the quarter-car. Then, consequent analyses is made how the dynamic characteristics of the car affect the human body vibrations.



Applying Newton's 2nd law to the quarter car model, the following dynamic equations are obtained as follows:

$$m_s Z_s^{''} + C_s(Z_s^{'} - Z_u^{'}) + k_s(Z_s - Z_u) = 0$$
$$m_u Z_u^{''} - C_s(Z_s^{'} - Z_u^{'}) - k_s(Z_s - Z_u) + k_t Z_u = k_t w$$

Figure 4 Concepts to convert and validate the equivalent analogy

Assume that *w* be the vertical deviation of the road profile, Z_s be the displacement of the car body, and Z_u be the displacement of the axle. The subscript s and u means the sprung and unsprung mass, respectively.

Taking the Laplace transform for the above motion equation, then

$$M_s s^2(Z_s(s)+k_s(Z_s(s)-Z_u(s))+C_s(sZ_s(s)-sZ_s(s))=0 \quad M_u s^2(Z_u(s)-k_s(Z_s(s)-Z_u(s))-C_s(sZ_s(s)-sZ_s(s))=k_t(w(s)-Z_u(s))$$

From the above equation, the transfer function H (s) is derived as the ratio of the body's acceleration with respect to the road profile (*w*).

$$H(s) = \frac{body \cdot position \ (Z_s)}{road \cdot profile \ (w)}$$
$$= \frac{Z_s(s)}{w(s)}$$
$$= \frac{k_t(C_s s + k_s)}{d(s)}$$

Where,

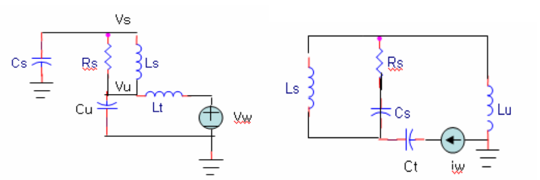
$$d(s) = m_u m_s s^4 + (m_u + m_s)C_s s^3 +$$
$$[(m_u + m_s)k_s + m_s k_t]s^2 + k_t C_s s + k_t k_s$$

When the quarter-car move a speed over the profile, the transfer function is changed into

$$H(s) = \frac{body \cdot accelerati \quad on \ (Z_s'')}{road \cdot profile \ (w)}$$
$$= \frac{Z_s''}{w(s)}$$
$$= \frac{s^2 k_t(C_s s + k_s)}{d(s)}$$

4. RESULTS

Figure 5 shows the equivalent circuit of the mechanical quarter-car where a) is based on the force-current analogy and b) on the force-voltage analogy.



a) force-current analogy b) force-voltage analogy

Figure 5 Equivalent electrical circuit of the quarter-car

From the electrical quarter car model, the transfer function i_s to i_w is derived as follows:

$$H(s) = \frac{body \cdot current \ (i_s)}{road \cdot current \ (i_w)}$$
$$= \frac{I_s(s)}{i_w(s)}$$
$$= \frac{k_t(C_s s + k_s)}{d(s)}$$

Here are the procedures to estimate the body acceleration with respect to the road profile based on quarter-car model.

1) generate a current $i_w(t)$ due to road profile

2) integrate the current to get the charge $q_w(t)$

3) insert the charge $q_w(t)$ into the quarter-car

4) measure a voltage across $v_{ls}(t)$ the inductor Ls

5) determine the current variation (di_{ls}/dt) through the inductor by the voltage $v_{ls}(t)$ divided by the Ls

6) finally, record the result 5) according to the result 3)

The result 6) will tell the body acceleration due to the road profile. The figure 6 shows the procedures that are explained in the above.

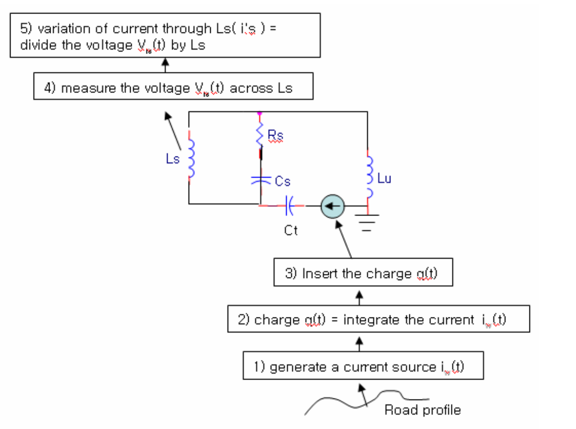


Figure 6 Procedures to build the quarter car

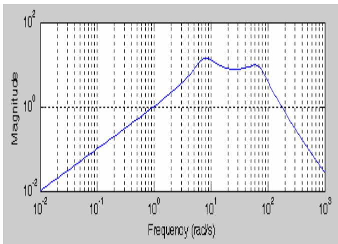


Figure 7 Acceleration of the quarter-car's body

The figure 7 shows the quarter-car body's acceleration characteristics by using MATLAB program. The figure 8 shows the frequency responses of the car body.

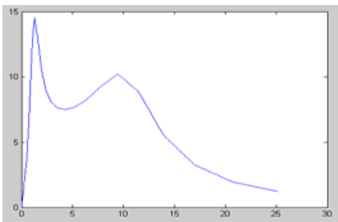


Figure 8 Zs(Frequency responses of car body)

For the first time, the electrical quarter model is designed and is proposed to implement by the electrical circuit components. Before the implement of the quarter car model, the simulated results are matched with the mechanical car.

As a future work, the electrical model will expand to the whole combined model including human body, quarter car, and road profile. The purpose of this research is to design a new measurement and management technology focused on human's perception, not on the road profile.

** This research work is supported by the smart highway research fund.

5. REFERENCES

[1] American Society of Testing and Materials, "Test method for measuring pavement roughness using a profilograph" ASTM-E 1274

[2] Gillespie, T.D., M.W. Sayers, and L. Segel, *Calibration of Response-type Road Roughness Measuring Systems*, NCHRP Report 228, TRB, National Research Council, Washington, D.C., 1980.

[3] Sayers, M.W., On the Calculation of International Roughness Index from Longitudinal Road Profile. In *Transportation Research Record 1501,* TRB, National Research Council, Washington, D.C., 1995, pp. 1 - 12.

[4] Michael W. Sayers, Thomas D. Gillespic, and Cesar A. V. Queiroz, World Bank Technical Paper Number 45, 1982

[5] Directive 2002/44/EC of the European parliament and of the council of 25 June 2002

[6] Paterson, W.D.O. and T. Wanatada. Relationships between Vehicle Speed Ride Quality and Road

[7] Potter D. An Investigation of Car Users' Perceptions of the Ride Quality of Roads. *Road and Transport Research*, 1(1), 1992, pp.6-26.

[8] Fred Mannering, "A statistical analysis of factors associated with driver perceived road roughness on urban highways", research project T1803, Task 28 highway roughness, June, 2002

[9] Johan Granlund, "Health Issues Raised by Poorly Maintained Road Networks", Swedish Road Administration Consulting Services, March, 2008